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Integrated stochastic life cycle benefit cost analysis of hydronically-heated apron pavement system

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Keywords

Winter airport operations, Hydronically heated pavement systems, Stochastic economic analysis, Monte Carlo simulation, Sensitivity analysis

Disciplines

Civil Engineering | Transportation Engineering

Comments

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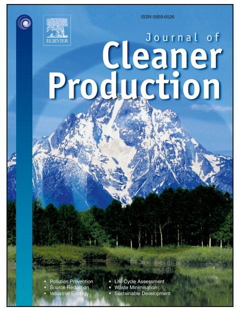

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Integrated Stochastic Life Cycle Benefit Cost Analysis of Hydronically-Heated Apron Pavement System

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Abstract

Transportation infrastructure is greatly impacted by ice and snow, adding enormous costs to the American economy. Because of their sustainability benefits, heated-pavement systems (HPS) continue to gain attention as a potential alternative to conventional snow removal operations, and the main goal of this paper is to assess the economic feasibility of hydronically-heated pavements systems (HHPS), one type of heated pavements, for use at apron areas of commercial airports. Both benefits and expenses associated with use of HHPS for snow and ice removal were identified and quantified in monetary terms using a stochastic economic analysis method, and a sensitivity analysis approach was used to determine particular variables that significantly influence overall economic viability of HHPS. The findings suggest that, despite high capital costs, HHPS use at airports might be economically feasible. The results from the sensitivity analysis indicate that airport size, in the context of number of aircraft operations, strongly affects the benefit-cost ratio of HHPS use.

Author keywords: Winter airport operations; HydronicallyHeated pavement systems; Stochastic economic analysis; Monte Carlo simulation; Sensitivity analysis

1 Introduction

In recent years, there has been a stronger focus on either investing in new infrastructure systems or retrofitting existing infrastructure systems designed and operated to be more resilient to natural and/or man-made extreme events (de Azevedo et al., 2018; Erker et al., 2017; Li et al., 2018; Rochas et al., 2015; Valenzuela-Venegas et al., 2018). Uninterrupted operation of critical transportation infrastructure systems like airports during such events is essential (Chang et al., 2014). Flight delays are a widespread challenge impacting the economy of every country, including the United States, and it is estimated that transportation delay costs came to approximately 32.9 billion dollars in 2007; it was estimated that this translated into a nearly 4 billion dollar reduction in the U.S. gross domestic product (Ball et al., 2010). Approximately one-third of delayed flights, including in the winter season, between September 2016 and August 2017 in the U.S. were due to weather conditions (U.S. Department of Transportation, 2017). Removal ice and snow from paved surfaces at airports is typically done by snow removal machinery and treatment of pavement surfaces with deicing and anti-icing chemicals (Baskas, 2011), and such conventional procedures are both labor-intensive and time-consuming, with deicing chemicals potentially causing long-term durability issues for pavements (Shi et al., 2009). Moreover, chemicals can contaminate water runoff from airports and thereby negatively impact the environment (Shen et al., 2017; Wang et al., 2006). Since addressing such socio-economic issues could help expand the set of experiences involving cleaner production, a sustainable alternative method for ice and snow removal would be most desirable in helping reduce transportation delays and consequently improving the U.S. economy. According to (Xu et al., 2018) hydronically-heated pavement systems are cleaner and more sustainable alternatives to the conventional ice and snow removal methods. Moreover, safety concerns due to snowfall and frost could also be addressed by HHPS installation.

The Federal Aviation Administration (FAA) has established operation-time-related criteria for clearing ice and snow related. For example, commercial airports with a number of airplane operations representing more than 40,000 passengers should be equipped to clear one inch of snow or ice from Priority 1 areas, i.e., runway, taxiways, and aprons (FAA, 2016), within one half hour.

Since apron areas typically require increased labor-intensive activities such as luggage handling and plane refueling, using smaller-sized equipment there could also make the snow removal process slower and less effective, propagating delays, and there are safety concerns on aprons particularly due to the presence of labor-related activities associated with snow-removal machinery. Such issues may inspire the use of pavement heating, especially at apron locations. To overcome winter maintenance-related problems such as environmental effects of de-icers, fuel and energy waste, safety concerns, and traveler delays, two possible heated-pavement solutions have been proposed in recent literature: (1) electrically-conductive concrete (Abdualla et al., 2016), and (2) hydronically-heated pavement systems (HHPS) (Pan et al., 2015). This study explores the use of HHPS, the most mature of such technologies with which construction contractors have greater familiarity.

“Hydronic heated pavement surfaces may be achieved by circulating heated fluid through a series of pipes running beneath the pavement” (Liu et al., 2007) (Figure1). Boilers fueled by natural gas or geothermal energy are typically used to supply warm water for such systems.

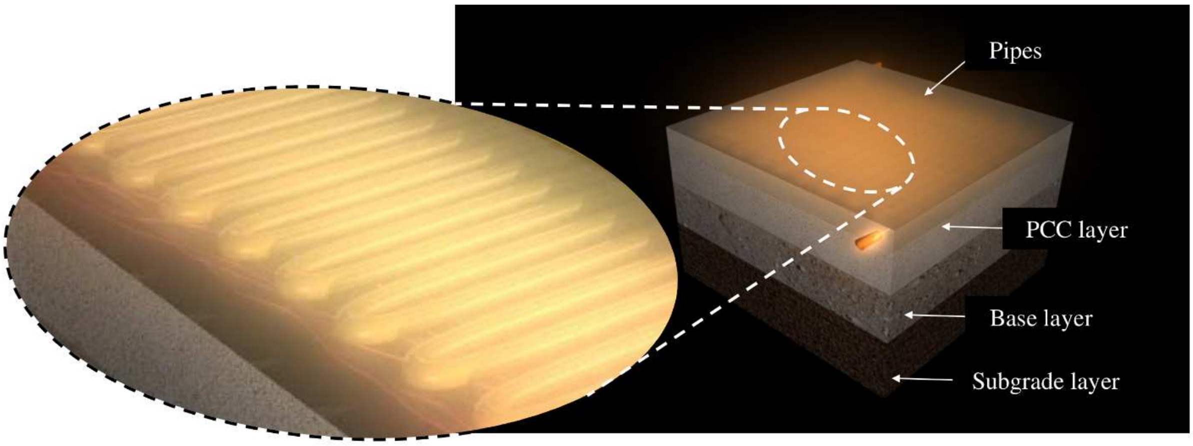


Figure 1 Details of a hydronically-heated pavement system (HHPS)

Application of HHPS for ice and snow removal operations has been reported as being effective and successful in European transportation infrastructure systems; in the U.S. heated pavement was implemented for the first time on a bridge deck in Oregon (Thurston et al., 1985), and since that time HHPS have been widely-used worldwide (Pan et al., 2015). However, before HHPS would be considered for airport implementation, it is necessary to evaluate the prospective energy and cost effects of such systems, and the literature in this area does not reflect much research attention given to these aspects to date (Pan et al., 2015).

In view of this scarcity, the main goal of this paper is to assess the economic feasibility of HHPS for apron applications in commercial airports. To achieve this objective, the potential benefits of HHPS implemented using Portland Cement Concrete (PCC) pavements were examined for two commercial airports, one a large-hub facility and the other a small-hub facility. The findings of this paper can help readers achieve better understanding of the different costs and benefits associated with snow clearing using HHPS with natural gas as its primary energy source. The methodology described herein can also be applied to other airports and used as a decision-making tool in evaluating potential adoption of this alternative technology.

2 Airport Site Selection

It is naturally to be expected that commercial airports in areas that experience a large snowfall would benefit most from HPS installation, so airports with an average yearly snowfall more than

90 cm per winter and ice/snow removal operations averaging requiring a minimum of 20 days per winter were identified as candidates for this study. Among the candidates, and particularly since airports in close geographical proximity were preferred for facilitatation of site visits, the following two commercial airports were selected for this analysis:

a) Minneapolis/Saint Paul International Airport (MSP), Minneapolis, MN, a large hub airport experiencing nearly 17 million enplanements in 2017 (1% of total U.S. enplanements) (Schaufele et al., 2017). MSP has one airfield with four runways, all operational during winter storms. MSP was the 17th busiest airport in the U.S. in 2017 based on its volume of air traffic (BTS, 2017a).

b) Des Moines International Airport (DSM), Des Moines, IA, is a small-hub airport experiencing marginally more than 1.1 million enplanements in 2017 (Schaufele et al., 2017) and daily supporting nearly 220 daily aircraft operations. DSM has two runways, both operational during winter season.

3 Economic Analysis Approach

Deterministic economic analysis approach is a decision-making method that uses discrete values and produces a single-value output. The important factor in such analysis is benefit-cost ratio (BCR), "*calculated by dividing the net benefits by net costs*" (FHWA Pavement Division, 1998). If the BCR of a potential project is greater than one, the investment on the project is considered to be an economically viable choice for investors (FHWA Pavement Division, 1998). "*The outcome of a deterministic LCBCA depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having potential for introducing error into the results*" (Gransberg and Kelly, 2008), and decision-makers must know the effects of such errors on the outcome of the LCBCA (Ali Nahvi, 2017; Asiedu and Gu, 1998; Daghighi et al., 2017; Gransberg and Kelly, 2008; Gransberg and Scheepbouwer, 2010; Nahvi, 2017; Nahvi et al., 2018; Sri, 2017). The issues listed, associated with a deterministic economic analysis approach, can often be resolved using stochastic life-cycle cost model development (Daghighi and Nahvi, 2014; Touran and Wiser, 1992).

3.1 The Stochastic Economic Analysis Model

The stochastic life-cycle assessment method, often used for sustainable infrastructure management (Banar and Özdemir, 2015; Batioja-alvarez et al., 2018; Ceylan et al., 2018; Gransberg and Scheepbouwer, 2010; Kucukvar and Tatari, 2012; Noshadravan et al., 2013; O'Born, 2018; Pittenger et al., 2012), was used in this paper to determine HHPS financial viability, as described in the following section. "*The stochastic LCBCA approach uses Monte Carlo Simulation (MCS) and allows input variables to vary through their probability distributions based on recent historical and regional changes*" (Kucukvar et al., 2014). Figure 2 illustrates the steps followed in this study for forming such a stochastic LCBCA framework. Major costs and benefits with use of HHPS were listed based on discussions with FAA officials and DSM and MSP airport mangers. Different costs and benefits of using HHPS were calculated, followed by Monte Carlo Simulation (MCS) to evaluate how changes in values of certain variables impact the benefit-cost ratio under a given set of assumptions. "*MCS supports quantification of the range of possible BCR values by performing sensitivity analysis to identify the individual impact of each input variable on the overall BCR model*" (Touran and Wiser, 1992), and BCR results were displayed using a probability density graph.

To estimate costs/ benefits related to HHPS, different types of data were gathered. Specifically, data related to the number of operations, the frequency of delays, and each delay's duration, along with capital, operational, and maintenance costs of traditional methods, were collected for economic analysis. Since direct data collection from each airport related to the frequency of delays occurring at each airport and their causes was not achievable due to unavailability of such data, most of the required delay-related data were obtained from publicly-available sources, i.e., the Bureau of Transportation Statistics (BTS) and the Research and Innovative Technology Administration, consistent with the BTS definition: "*A flight is considered delayed if it arrives 15 or more minutes later than its scheduled time*" (BTS, 2017b). While there can be many reasons for flight delays, on average for all airports, the fraction of weather-related delays occurring at a point of departure, is approximately 5% of all delays. While such delays are usually caused by extreme weather such as tornadoes, blizzards, or hurricanes (Bureau of Transportation Statistics, 2017), since most weather-related flight delays during winter are due to snowfall (WeatherBill, 2017), forthe purposes of this study delays relative to ice and snow removal operations can be assumed to be approximately 3% of total operations (Anand et al., 2017). The percentage of delays related to snow/ice removal was also added as one of the inputs to the stochastic economic analysis model. After discussions with the airport managers, costs and benefits were also assumed to vary as a function of the area considered.

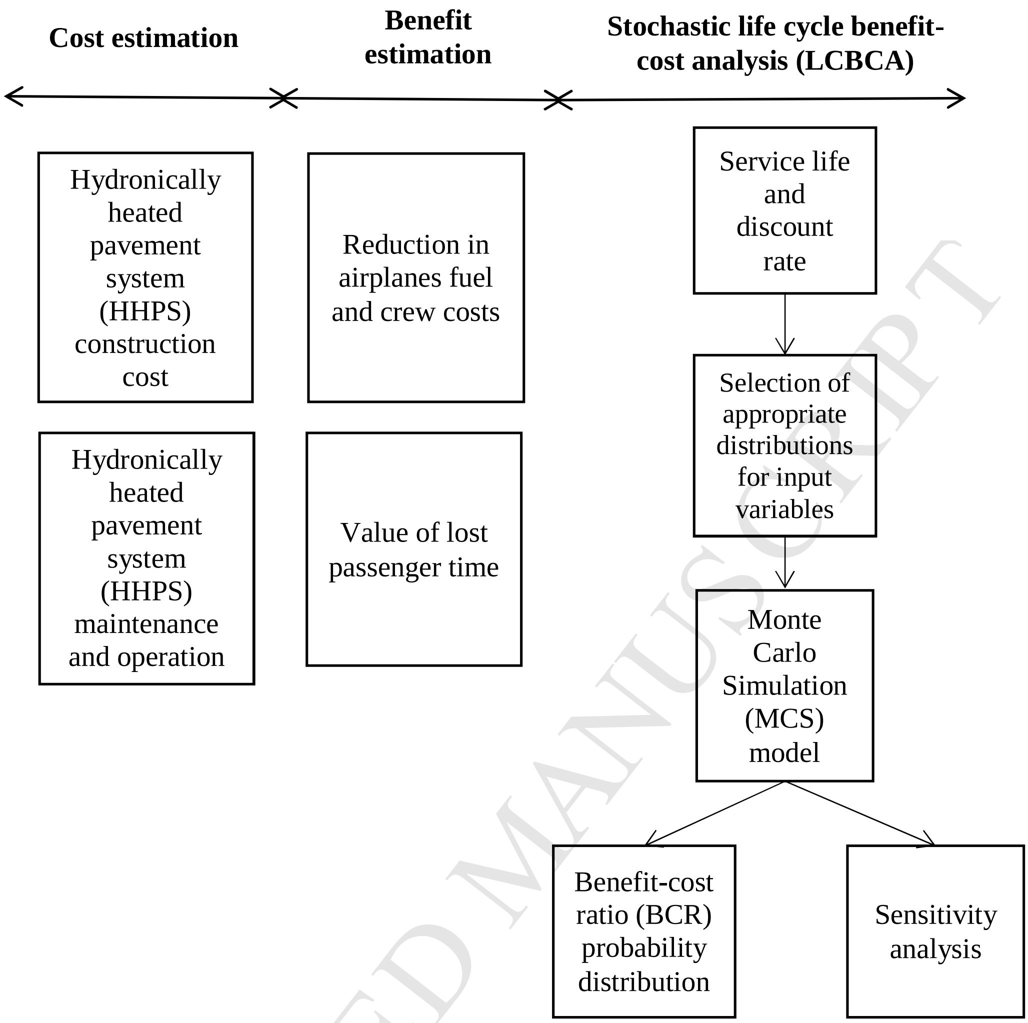


Figure 2 Methodology followed in the study to conduct stochastic economic analysis

4 Cost estimation

This section describes costs related to removal of snow using HHPS and is specifically related to cost estimation. The costs considered included initial, operational, and maintenance costs.

4.1 Capital cost

Initial construction cost is one of the main components of LCBCA (FHWA Pavement Division, 1998). The initial construction costs of HHPS were obtained from project bid tabs provided by Midwestern HHPS contractors. Bid data provide a simple, reliable, and quick source for estimating unit costs (Tehrani, 2016). The data set used in this analysis contained bid records obtained over the previous two-year period (September 2015 to December 2017). Figure 3 shows how unit costs of various HHPS projects were distributed during this period, and also shows the unit cost of HHPS implementations both at airfields and at other locations (hospitals, rest areas, sidewalks, etc.). To determine significant differences between unit costs of projects at airfields and those at other HHPS installations, projection of t-tests can be useful statistical tools for examining differences between two population means. A statistical t-test was conducted using a selected confidence level of $(1 - \alpha) = 0.05$, meaning that a result is not considered significant if $p < 0.05$. All the unit cost values were plugged into the MCS model to capture variations in installation costs arising from different concrete thicknesses, location factors, project specifications, and heating system types.

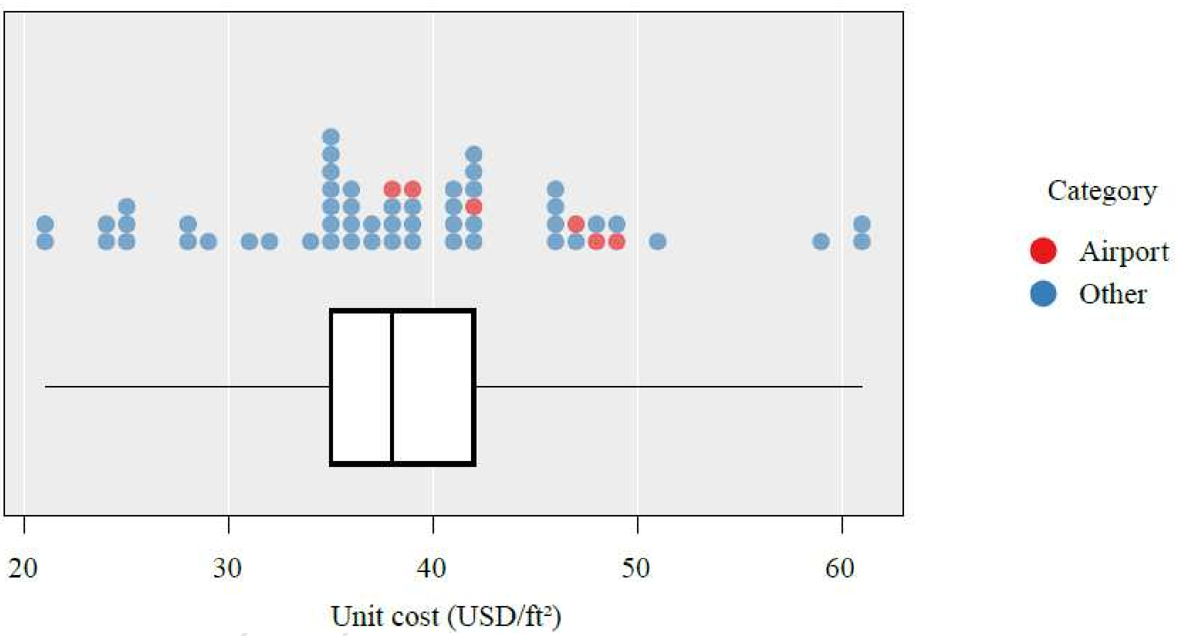


Figure 3 Construction unit cost for 58 hydronically-heated pavement (HHPS) projects (provided by heated pavement contractors in Midwest)

4.2 Maintenance

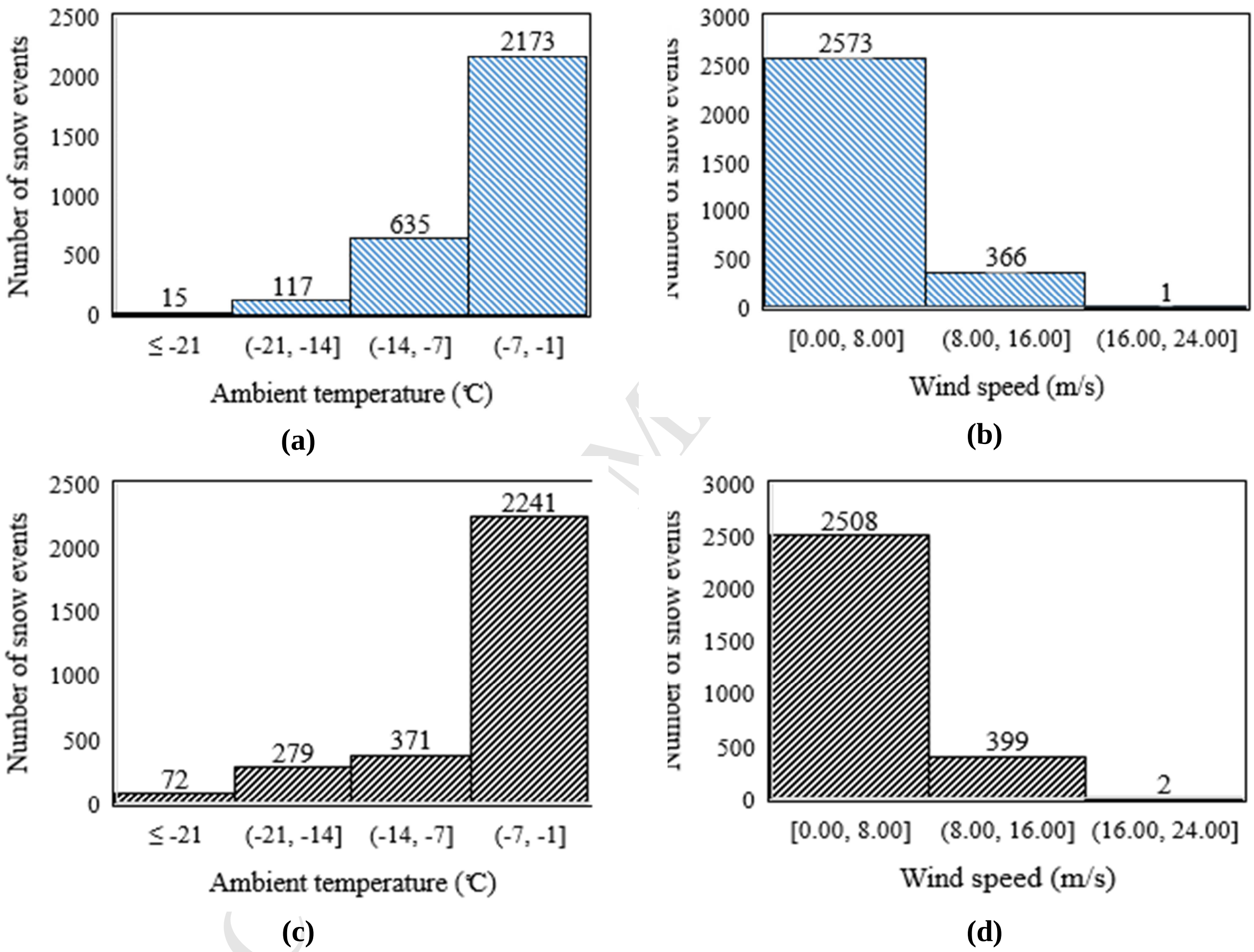
Based on information obtained from DSM airport managers, costs of maintaining large-scale hydronic airfield heated pavement system can be assumed to be about 1% of its construction cost. Note that, because historical records regarding costs associated with maintenance of HHPS subject matter were unavailable, expert opinions (i.e., from DSM maintenance managers) were used to quantify maintenance costs of HHPS. "*Expert Judgement techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties, or the uniqueness of the situation, it has been impossible to make enough observations to quantify the model with real data*" (Bedford et al., 2016).

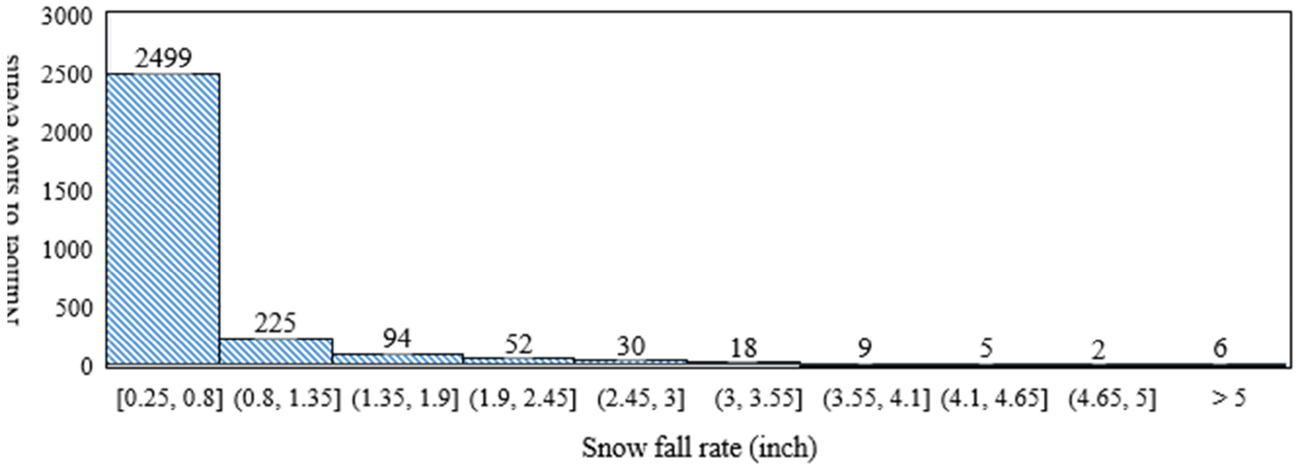
4.3 Operational costs

With respect to operational costs, since the assumption was made that a HHPS would be operated using automatic controllers and switching equipment, no labor costs would be required, so operational costs were assumed to be only the cost of energy (i.e., natural gas) essential to warm the anti-freezing liquid flowing through the pipes and the cost of electrical power required by the controlling system. To measure the amount of energy (i.e., volume of natural gas needed to melt ice and snow), the design heat load was first estimated, as described in the following section.

4.3.1 HHPS Energy Consumption

There have been several previous studies on energy modeling of HHPS. Xu and Tan studied the energy demand of HHPS under different weather scenarios, including extreme weather conditions (Xu and Tan, 2015) consistent with other studies on HHPS energy consumption (Xu et al., 2018). These scenarios were established by selecting different combinations of ambient temperatures ranging between -6 and -30°C, a wind-speed range of 4 to 8 m/s, and snowfall rates ranging from 0.2 to 0.8 mm/h. In seeking to use results from the aforementioned studies for the current paper, the weather conditions at the case study locations were investigated using temperature, wind speed, and snowfall rate recordings obtained from automated surface-observing systems during snow events at DSM and MSP between 1987 and 2017 (ASOS, 2018); there were 2,940 and 5,567 data points during snow events at DSM and MSP, respectively, over this period. As shown in Figure 4, all the temperature values, 88% of the wind-speed readings, and 85% of the snowfall rate values during the investigated snow events at DSM fell into similar ranges of weather conditions as those studied by Xu and Tan (2015). Similarly, in the case of MSP, all ambient temperatures, 93% of wind speeds, and 89% of snowfall rates were in these range. Since most of the weather condition recordings during snow events for both DSM and MSP had been previously considered in Xu and Tan's study, their estimates of the distribution of total energy consumption of HHPS were used in this study.





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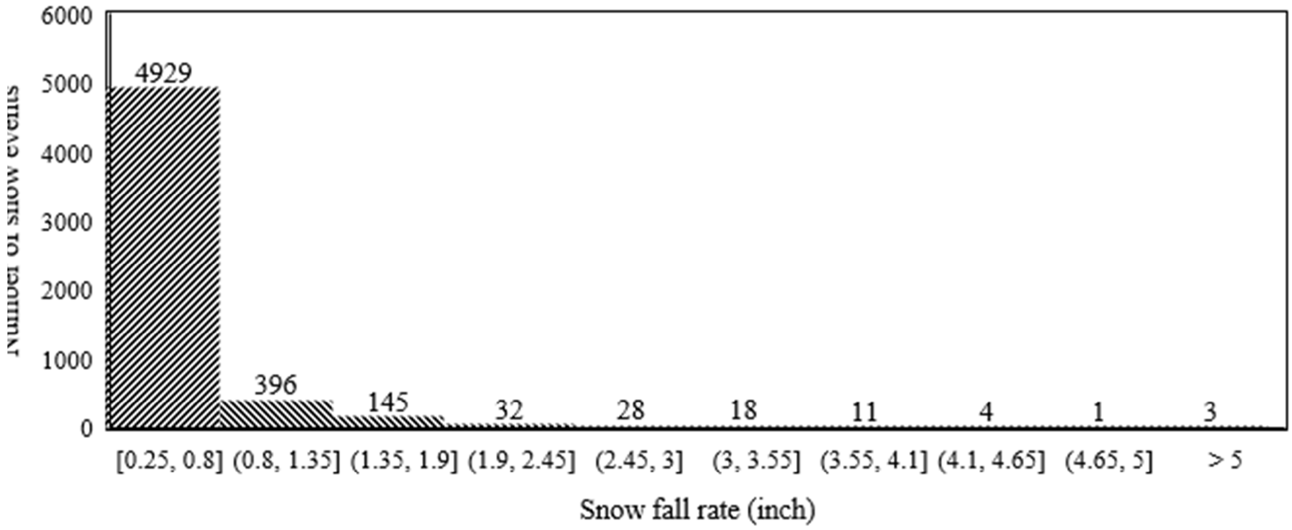

(f)

Figure 4. Histogram of climatic conditions during snow events from 1987 to 2017 for case studies (ASOS, 2018): *(a)* Ambient temperature (°C) in DSM, *(b)* Wind speed (m/s) in DSM, *(c)* Ambient temperature (°C) in MSP, *(d)* Wind speed (m/s) in MSP, *(e)* Snow fall rate (inch) in DSM, *(f)* Snow fall rate (inch) in MSP.

Idling time, defined as the time needed for a system to increase the pavement surface temperature to the melting point of 0.5°C (ASHRAE, 2001), was used as a criteria for evaluating a system's capability for melting snow and preventing snow accumulation under different weather conditions. The shorter the idling time, the higher the heating capacity of the boiler for heating the fluid running through the embedded pipes. Among all weather parameters, ambient temperature has the strongest effect on idling time (Xu and Tan, 2015). Since idling time provides a reliable picture of system performance, it has been taken as the main parameter in the design of HHPS. According to temperature recordings for DSM and MSP, if boilder heating capacities of 0.6, 0.9, 1.2, 1.5 and 1.8 kW/m^2 were considered, the worst-case scenario for idling time would be 150 minutes (Xu and Tan, 2015), and this conservative assumption was used in this paper in performing the operation cost analysis. Four possible scenarios for system performance were developed based on ambient temperatures lying within the ranges listed in Table 1. This study assumed that, for each snow event, the system would start 150 minutes before that event and run continuously until the end of the day.

Table 1 Assumptions and results of energy consumption assessment

Scenario	**Ambient temperature** (All temperatures for all snow events are within these bounds)	**Heating capacity of boiler required (kW/m^2)**	**Required Natural Gas (ft^3/m^2)**	**Probability in DSM**	**Probability in MSP**
A	> -6 °C	0.6	50	74%	67%
B	< -6 °C > -14 °C	1.2	98	22%	25%
C	< -14 °C > -22 °C	1.8	147	4%	8%
D	<-22 °C	System is not functional	0	1%	1%

If the ambient temperature was below -22 °C, the idling time would be more than 150 minutes (Xu and Tan, 2015). As shown in Table 1, for one percent of all snow events, the ambient temperature would be below -22 °C, the idling time would be greater than 150 minutes, and the HHPS alone would not be practical for melting ice and snow, so auxiliary snow removal machinery and crew along with the HHPS would be necessary to adequately remove airfield ice and snow under such extreme conditions..

Annual energy consumption costs can be calculated using Equation 1.

$$C = E_m \times A \times N_s \times e \times E_p \quad (1)$$

where C is annual energy consumption cost, A is HHPS paved area (m^2), E_m is average energy use (kWh/m^2), N_s is the number of snow events, e is the efficiency factor (0.85) (Cleaver Brooks, 2010; lo Storto, 2018), and E_p is price of natural gas (USD/kWh), (values obtained from U.S EIA, 2018). Since there are many uncertainties associated with annual energy consumption (i.e., $E_m, N_s, and\ E_p$), considering a discrete input for annual energy consumption cost in the economic analysis can introduce bias into the results. Issues associated with a deterministic annual energy consumption cost model (Eq. 1), including volatility of underlying commodity prices, was addressed by developing a MCS-based analysis whose results are presented in the Results and Discussion sections.

5 Estimation of Benefits for HHPS

In considering HHPS benefits, the effects of time lost from using conventional technologies during snow removal operations were investigated and projected into the financial values. The main anticipated benefits associated with HHPS field implantation studied in this paper were reduced passenger delay and reduced plane operating delay costs. The following sections describe the estimation of each such aspect.

5.1 Value of lost passenger time

The main factor to be accounted for is the collective lost time value by passengers who experience flight postponement, and a reduction in the associated costs would represent a major benefit of HHPS. To put the potential of this benefit into perspective, (Ball et al., 2010) estimated that, in 2007, domestic passenger flight delay costs were $16.7 billion (in 2007 dollars) imposed on the U.S. economy.

Note that passenger delay costs represent only indirect costs because aircraft operators in general offer no form of compensation (e.g., free meals or discount on accommodation) for snow-related flight postponement. Passenger costs due to delays were calculated according to air-traffic demand, with the number flights each day, the seats available on each plane, and a load factor estimate used to adjust the demand. "*Load factor is a measure of the use of aircraft capacity that revenue passenger-miles as a proportion of available seat-miles (ASMs)*" (BTS, 2017c). In 2017, the average load factor for U.S domestic air transports was 84.4 % (BTS, 2017c).

Also, since flight demand capacity is not constant over time and is on average anticipated to grow every year, the average passenger volume growth rate was considered to be 3.4% per year for the next twenty years, in line with an FAA prediction (Schaufele et al., 2017).

The value of lost passenger time is also related to trip purpose, so passengers were categorized into two groups: those traveling for personal/leisure purposes and those flying for business (Belenky, 2011). Table 2 shows the values of time per trip purpose considered in this study.

Table 2 Values of time per trip purpose on a delayed flight

Value of time (per hour)	Cost (US/ hour)	Passengers percentage based on trip purpose (%)	Number of passengers in a flight
Personal/leisure	36.1	59.6	74.5
Business	63.2	40.4	50.5

Passenger delay costs were estimated using Eqs. (2) and (3).

$$T_d = N_d \times P_s \times P_g \times A_d \times 120 \times 99\% \quad \textbf{(2)}$$

where T_d *is* total lost time per winter season, N_d is number of aircraft operations each day, P_g is the passenger growth rate, P_s is the number of delays related to snow/ice removal operation, and A_d is the duration of each delay (hours).; the value 120 value reflects an average of 30 days per month multiplied by 4 months per winter season. For one percent of the scenarios, because use of HHPS alone is occasionally not a practical approach for ice and snow melting (as mentioned in the HHPS Energy Consumption section), benefits were estimated for 99% of the snow events.

$$A_m = T_s \times L_f \times P_p \times T_p \times V_t \times 99\% \tag{3}$$

where A_m is the yearly monetary value of traveler time (USD), L_f is the load factor, T_s is the total number of seats in each plane, P_p is passenger percentage based on trip purpose, and V_t is monetary value of time consistent with the trip purpose. Similar to the reduced passenger delay costs, benefits were estimated for 99% of the snow events.

5.2 Reduction in aircraft operating delay costs

With respect to aircraft operating delay costs, the key factors contributing to the anticipated reduction in cost of using HHPS are reduced aircraft fuel wastage and reduced extra crew working hours. For aircraft operating delay costs, the number of delayed air travels was estimated using the same method as for estimating value of lost passenger time. With respect to the particular points at which such delays occur, there are three types of aircraft delays: mid-air, gate, and ground delays. Mid-air delays will result in the highest amount of fuel wastage; gate and ground delays will be related to idling fuel wastage only. The cost of mid-air delays is approximately $4,449/h, and the costs of ground and gate delays are $2,169/h and $1,457/h, respectively (Mcgormley et al., 2016) (adjusted for 2017 values). Each delay category would contribute a different percentage to the total delays and therefore incur different costs. Because such information was unavailable, the assumption was made that all types of postponements would occur in the same proportion, yielding an average value of a $2,850/h cost experienced by airlines during ice/snow related delays. The yearly (for the four months considered) cost to airlines due to snow removal operation can then be calculated by multiplying this value by the total number of operations during the winter months. The annual operation growth rate for subsequent years is also included in these calculations.

6 Service Life and Discount Rate

FAA economic analysis manual (FAA, 1999) for major airport infrastructure projects suggests adoption of a 20-year economic life span beyond completion of construction. In addition, for capturing discount-rate fluctuations in the economic analysis and evaluating discount-rate sensitivity with respect to the BCR, the previous twenty-year (1997 to 2017) discount rate data from the Federal Reserve (Federal Rserve, 2018) was obtained, fitted to the appropriate probability distribution, and introduced into the model.

7 Selection of Appropriate Distribution of Variables

A range of different types of data were collected to estimate benefits and costs associated with use of HHPS. Specifically, these include data related to the number of operations, the number of delays, and the duration of each delay, along with capital, operational, and maintenance costs of traditional methods. Table 3 includes a summary of the data utilized for ECON cost/benefit estimations. The values of some of the inputs were common to both case studies, while the values of some variables (e.g., the duration of each delay, the ambient temperature, and the amount of snowfall in one hour) differed.

Table 3 Data collection summary for HHPS benefits/costs estimation for studied airport

Category	Benefit/cost by shifting from CSRS to HHPS	Item	Source
Benefits	Value of lost passenger time	Annual number of delays	(BTS, 2017a)
		Total delay hours in winters	(BTS, 2017a)
		Load factor	(Schaufele et al., 2017)
		Percentage of passengers traveling for business	(Belenky, 2011)
		Value of time for leisure	(Belenky, 2011)
		Value of time for business	(Belenky, 2011)
	Reduction in fuel consumption and crew costs	Mid-air delays	(Mcgormley et al., 2016)
		Ground delays	(Mcgormley et al., 2016)
		Gate delays	(Mcgormley et al., 2016)
		Total delay hours in winters	(BTS, 2017a)
Costs	HHPS Operational Costs	Construction cost	Discussion with contactors (Figure 2)
		Price of commercial natural gas	(U.S. Energy Information

		Administration, 2018)
	Annual number of snow events	(NOAA, 2017)

"*Determining the appropriate probability distribution for each input variable is an important step in the stochastic LCBCA approach*" (Anand et al., 2017). A maximum likelihood method was used to fit the variables to a distribution, and the best fit distribution was chosen based on a chi-squared goodness-of-fit test (Pearson, 1992). For percentage of weather-related delays associated with limited sample data, a triangular distribution, appropriate for variables with limited data (Gransberg and Kelly, 2008), was used. The variables obtained using historical data and the best fitted distributions for the input variables are shown in **Error! Reference source not found.** To represent the amount of variation in the input variables, standard deviations are also reported in the Table 4.

Table 4. Variables distributions for Monte Carlo simulation (MCS)

Common variables to both DSM and MSP				
Input variable	**Distribution**		**Description**	
E_c - Electricity use (W/m^2)	Discrete		Table 1	
Discount rate (%)	Pareto		Std = 1.1 α = 3.1	
T_p - Trip purpose (-)	Discrete		Table 2	
Uncommon variables				
Input variable	**Distribution**		**Description**	
	DSM	MSP	DSM	MSP
E_p - Gas price (USD)	Triangular	Triangular	{3.1,3.8,14.2}	{5.3,6.7,9.9}
N_s – Number of snow events	Normal	Normal	μ= 16 Std = 7	μ= 25 Std = 9
N_d - Number of operations in each day (-)	Normal	Normal	μ= 198 Std = 23.3	μ= 605 Std = 47.9
A_d - Duration of each delay (hours)	Normal	Logistic	μ=0.78 Std = 0.21	μ=0.95 Std = 0.36

8 Results and discussion

A MCS was conducted to determine a probabilistic energy consumption cost and LCBCA for each case study. Using Equation 1 and the distributions shown in Table 4, cumulative probability curves of the energy consumption costs of DSM and MSP were estimated and are shown in Figure 5.

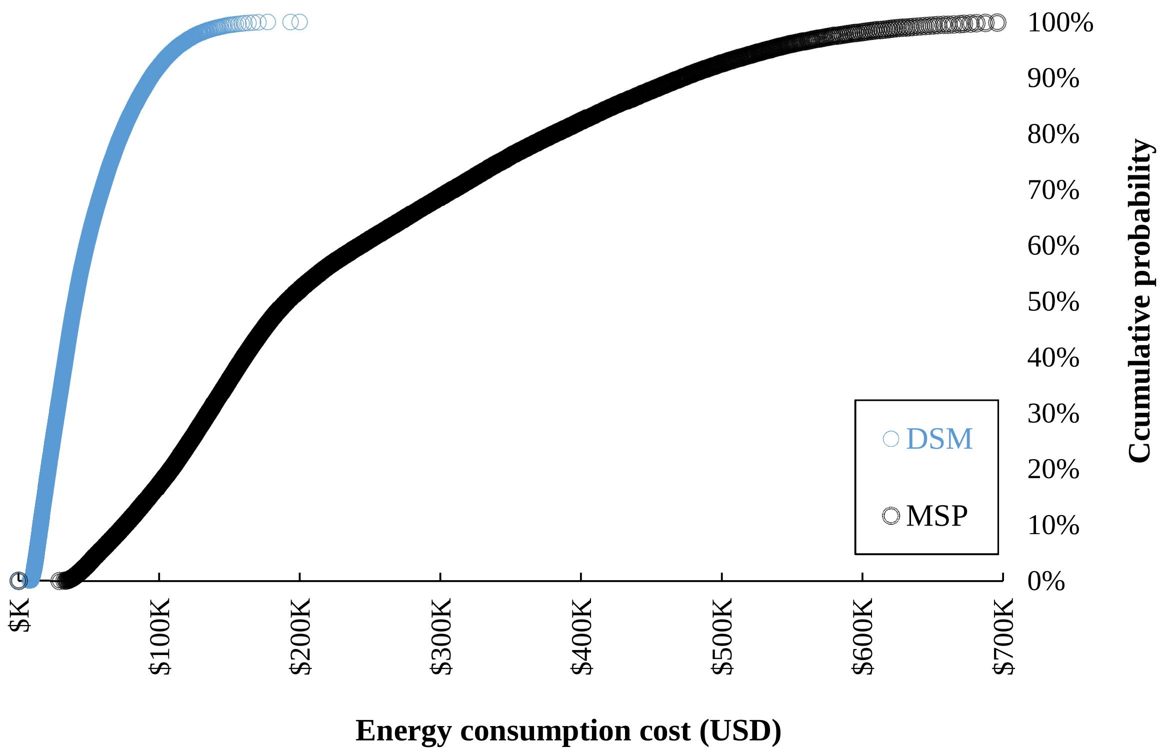

Figure 5 Energy consumption cost (USD) for an apron area

As shown in Figure 5, the annual median energy consumption costs of HHPS at MSP (1.96 million USD) is almost six times larger than that for DSM (0.34 million USD). This difference is mostly related to cumulative apron area size in MSP, almost three times bigger than that of DSM. To perform the same base comparison, the median energy consumption per square meter was calculated by dividing median energy consumption costs by size of apron area, yielding a median energy consumption per square meter for MSP of 4.2 USD/m^2, 1.7 times larger than for DSM (2.4 USD/m^2), with the main cause for this difference related to the greater number of snow events at MSP each year (almost sixty percent more than for DSM).

Another simulation was conducted to measure LCBCA for each case study. Table 5 describes the probability density function for the BCR at DSM and MSP, reflecting a possibility that, when implementing HHPS, benefits would compensate for costs in all possible scenarios in DSM and MSP, with the median value of BCR in the case of MSP case almost 60 % higher than for DSM.

Table 5 BCR summary statistics and likelihood of occurrence

BCR Summary Statistics			Likelihood of Occurrence		
	DSM	**MSP**		**DSM**	**MSP**
Minimum	1.08	2.02	**95%**	2.49	4.50
Maximum	2.84	5.09	**85%**	2.30	4.18
Mean	1.81	3.13	**75%**	2.07	3.77
Std. Dev	0.40	0.67	**10%**	1.21	2.37
Median	1.71	3.13	**5%**	1.19	2.27

As mentioned in the discussion of the economic analysis approach, another output produced by running MCS is stochastic sensitivity analysis to identify the influence of each input variable on the overall benefit-cost ratio. Such a sensitivity analysis was conducted to test the effects of changes in different parameters with respect to the final decision (Figure 6).

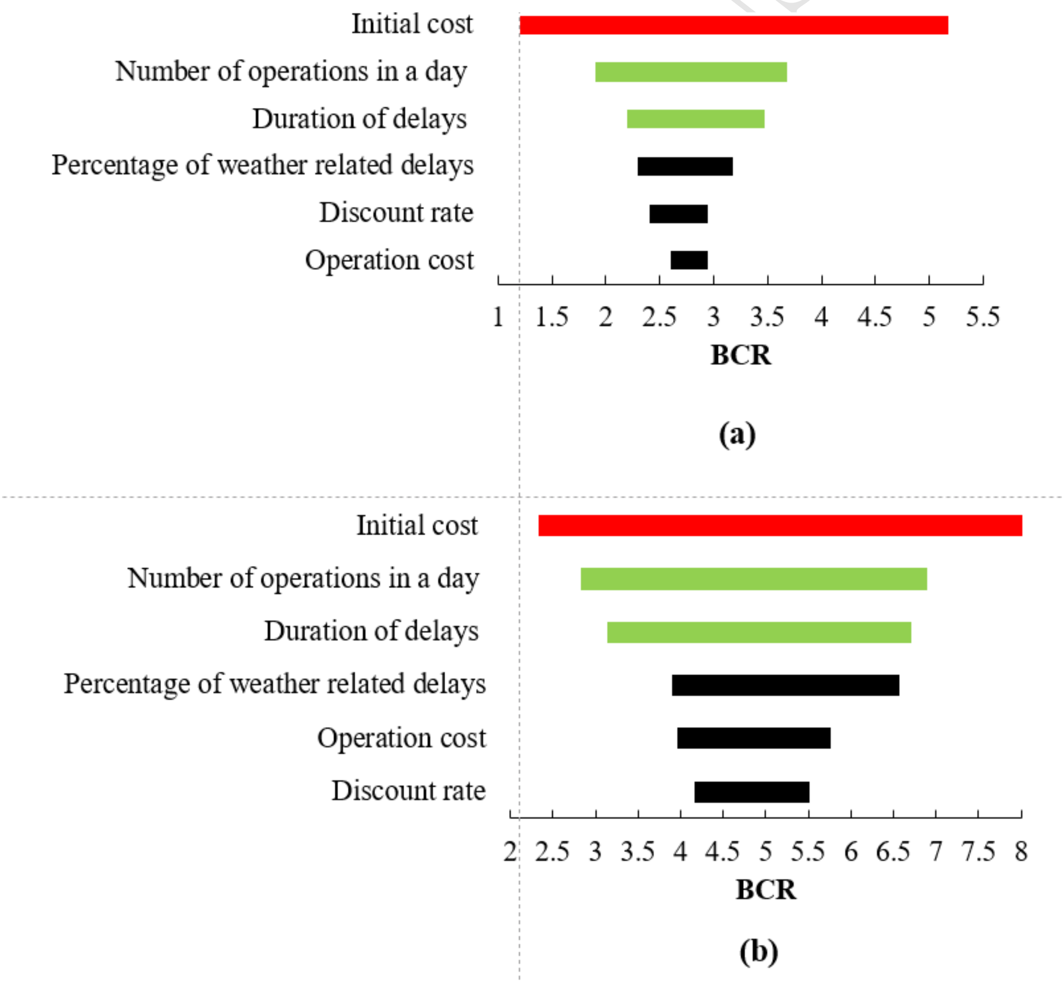

Figure 6 sensitivity analysis results (tornado graph); *(a)* DSM, *(b)* MSP.

BCR appears to be sensitive to initial installation costs independent of airport size. In fact, as shown in Figure 6, capital cost is the only variable that by itself drove the BCR to a value near 1.0 for the worst-case scenario related to the DSM case. In addition, while larger air-transportation terminals such as MSP seem to be even more sensitive to initial costs, in the case of MSP BCR remains above 2.0 for the whole range of initial costs considered in the analysis. At the same time, the findings suggest that the BCR of such large airports is also sensitive to both the number of operations and the delay durations. As can be seen in Figure 6, since the number of operations and delay durations seem to be among the major factors that drive the benefits of the HHPS for MSP, it is reasonable to conclude that the size of the airport in terms of the number of airplane operations would have a considerable impact on the BCR. Aside from a direct increase in benefits expected to result from a growth in the number of operations, it is also possible that economies of scale, with cost per unit of output decreasing with increasing scale, could impact results of the economic analysis, although such factors were not directly evaluated in this study.

9 Conclusion and recommendation

This study quantified costs and benefits associated with HHPS. The methodology described herein and the findings of this analysis can assist commercial airport managers in making better-informed decisions in selecting a suitable option among alternative adverse winter weather operational strategies. This paper also proposes a method for estimating energy consumption and operational costs of HHPS for large areas such as airport aprons. The following key recommendations based on this study's key findings are:

- From a cost-benefit perspective, while the use of HHPS is a potentially viable option for combatting airport snow and/or ice conditions, the HHPS cost-benefit ratio for an airport mostly depends on several site-specific airport characteristics, including the number of airplane operations and the HHPS implementation area, so the cost-benefit results of utilizing HHPS should be evaluated on a case-by-case basis.

- Because all airport aprons are not used at all times, the boiler capacity could also be designed to reduce initial costs by time-sharing its use among different areas. It is expected that future advancements in HHPS construction practices and technology would further decrease initial and operational capital costs. Future research can explore the potential of such technologies and associated and construction practices.
- Conceptually, HHPS implementation sufficient for snow/ice removal might be used in maintaining regular airport operations only in portions of apron areas. If site investigations and experimental studies can demonstrate that heating only a portion of the total apron area could help in reducing flight delays, the use of HHPS might prove to be considerably more cost-beneficial than originally estimated. This finding is especially important for smaller hub airports such as DSM.
- The methodology developed in this paper could be extended to examining the economic viability of other similar technologies, such as electrically-conductive asphalt/PCC concrete (Arabzadeh et al., 2018; Sassani et al., 2018) blended with superhydrophobic materials (Nahvi et al., 2017).

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